Solar Energy in Water Treatment Processes—An Overview

Ashish Unnarkat, Ayush Bhavsar, Samyak Ostwal, Pancham Vashi, and Swapnil Dharaskar

Abstract Water remains at the centre of human survival on the planet earth. Water availability and its consumption pattern in the world have drastically changed over the past few decades. The rising population and changes in the standard of living have put stress on the water bodies, and major countries around the globe are on the verge of facing serious water scarcity. Earth has an abundance of water but is not in usable form. It demands technologies that can provide fresh water for the people but must be economical, sustainable and less energy-intensive. Desalination is the solution, but the conventional techniques are energy-intensive processes and not eco-friendly. Solar energy has come out as a sustainable and greener energy source for carrying out desalination. Solar energy for desalination has been widely explored in recent times. Another major problem with developing countries is handling water-borne diseases, which lead to major health issues and fatalities. Solar energy comes to the rescue here, and its application for the disinfection of water will cater to the need for safe water, improving community health and providing a sustainable solution. The chapter presents a review on the application of solar energy in two broader domains of water treatment; (a) water desalination and (b) water disinfection. The chapter discusses the different types of solar integrated desalination technologies with their uniqueness and limitations. Recent developments for the most common desalination technologies of multi-stage flash (MSF), vapour compression (VC), multi-effect distillation (MED), and reverse osmosis (RO), and electro-dialysis (ED) are discussed. Solar energy-based technologies will prove to be an alternative to the current technologies in water treatment and disinfection, the price will remain the concern, but this will be overcome with the efforts and technological improvement in the field. Solar energy and its utilization in the water treatment process make its way as the potential solution for all safe and clean drinking water.

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1 Introduction

1.1 Water Scarcity and Treatment

As the population of the world is on the rise so does the demand for fresh water. With the current climate change scenario across the globe and the deteriorating environmental conditions, water scarcity will pose a serious challenge to the survival of human race on the planet (Seckler et al. 1999). In the regions of Asia and Middle East, the ground water level is falling at an alarming rate and the water table is hugely disturbed. There is an urgent need to focus the attention of both professionals and policy makers to find sustainable solutions so as to fulfil the demand of fresh water for the growing population. Renewable energies like solar energy are widely explored as the primary source of energy in the water treatment process. Solar has been a clean and green energy solution and is available in abundance from the nature. Currently solar energy is in used two domains of water treatment, one being desalination of the sea water and second being water disinfection. The solar power driven water treatment processes has come as a novel and sustainable solution to address the issue of fresh and safe water for all (Pugsley et al. 2016; Chandrashekara and Yadav 2017; Ullah and Rasul 2019; Curto et al. 2021). Currently, the solar based water treatment processes are in great demand but the real time applications and the economics gives a major setback to the process. However, the solar based process are promising and can be viable for the large scale production and the water costs will then be significantly reduced. The efforts in the direction will make the technology more durable and available for the societal benefits (Foran 2007; Pugsley et al. 2016; Curto et al. 2021).

1.2 Conventional Water Treatment Techniques for Desalination and Disinfection

Natural sources of water are getting polluted with rapid industrialization and human activities. The increased demand and overuse of water in the urban areas have worsened the situation of the available water resources, and the conventional water treatment plants are overburdened. Over the decades, the conventional treatment included methods like coagulation-flocculation, sand filtration, sedimentation, ozonation and chlorine-based disinfection to gain freshwater (Sarkar et al. 2007). But in recent times, the water bodies are getting contaminated with industrial waste and toxins from human activities, the water quality is abrupt, making the conventional plants inefficient for quality assurance. The significant drop in feed water quality has impacted the overall process. In the absence of a strong environmental protection framework and lawful practices, the contamination of water bodies is continuous in developing and underdeveloped nations. Several drawbacks or hardships in traditional water treatment plants are mentioned below:

a. Pollution of water bodies by industries which consists of pharmaceutical wastes, toxins, chemicals and fertilizers used in agro-based industries are generally not affected and completely removed by the traditional and conventional methods of water treatment, and these require advanced techniques for the remediation (Xia et al. 2004; Radjenović et al. 2008).
b. Separate biological treatment for removing the microorganism and bacteria's is to be incorporated. The case of the Mery-sur-Oise water treatment plant in France and the Cheng Ching Lake Water Works conventional water treatment plant are among those examples where algae and weeds were not removed from the water and caused several health issues (Yeh et al. 2000; Cyna et al. 2002).
c. Water produced from traditional treatment plants may be too hard and must be softened further. Traditional softening processes such as cold and hot lime softening and pellet softening require intensive consumption of lime and acids and will produce large quantities of sludge (Bergman 1995).
d. Chlorination methods that are used for disinfection remove viruses and bacteria, but prolonged exposure to the chlorinated water has severe health effects.

The conventional techniques for the desalination of water is through reverse osmosis (RO) desalination plants. However, the performance of RO membrane and its fouling resistance remains a challenging feature that deters its efficiency for the treatment. The water resources generally used for the desalination plants is sea water or blackish water. Seawater is generally rich in contaminants such as colloidal particulates, mineral salts, high microorganisms, natural organic material, oil and grease and hydrocarbons that require extensive pre-treatment plans (Bohn et al. 2009; Shekarchi and Shahnia 2019). If the pre-treatment process is not complete then these contaminants goes to the membrane unit and blocks the flow through the membrane and decrease the overall rejection. The pre-treatment processes that are widely preferred for the sea water RO plants is coagulation, flocculation, sedimentation, pH adjustment, chlorination, scale inhibition, dual media filter and dissolved air flotation, these are the conventional primary filtration methods employed in most of the water treatment plants. The pre-treatment provides the required feed water for the RO system though the parameters has to be tuned with the sea water quality (Amiri and Samiei 2007). The inconsistency in the quality of water, its flowrate, susceptibility of membranes to biofouling attacks and scaling are some of the shortcoming of the RO process that makes it slightly inefficient.

1.3 Application of Renewable Energy in Water Treatment

The use of domestic sources of renewable energy together with the implementation of energy-efficient technologies pave the way to sustainable solutions and overcome the dependency on conventional energy sources. These options would help curb the rise of greenhouse gas emissions and make countries less dependent on energy imports and face the repercussions of fossil fuel price fluctuations. The technological advances in the renewable energy sector will improve the economics. The renewable sources are available in abundance and will not face extinction as in the case of fossil fuels. This means that it would remain for the generations to come (Chandrashekara and Yadav 2017; Alnaimat et al. 2018; Zhang et al. 2018).

Renewable energy and energy-efficient technologies for water desalination can provide ideal solutions for large-scale desalination and treatment plants in both off-grid and on-grid areas. A large amount of energy that is required for the desalination can be provided from locally available renewable energy resources independent of whether they are directly produced and applied (e.g., solar thermal, geothermal direct use) or indirectly applied through an interim production of electricity (e.g., solar photovoltaic, electricity generation from wind or geothermal). This electricity can be used to power the desalination units. Coupling renewable energy with desalination technologies paves the way for meeting the demand for fresh water. Solar assisted water desalination and disinfection technologies and their classification if provided in Fig. 1.

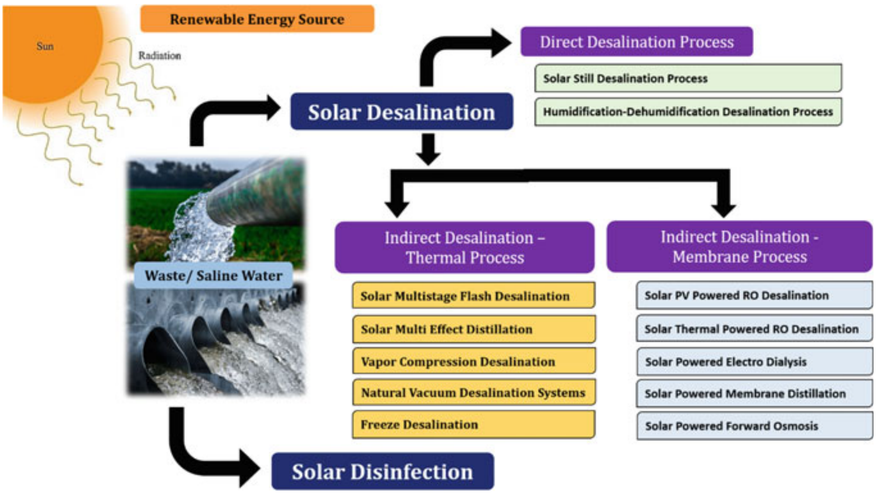

Fig. 1 Solar assisted water treatment

Water disinfection predominantly kills or deactivates the pathogens or micro-organisms in the water. Mostly chlorine-based disinfections are prevailing in practice that is not eco-friendly. Chemical-based disinfection has environmental consequences and also health effects. Ozone is another method that is employed in disinfection; however, it's not an economically viable option on a larger application. Boiling is considered to be one of the most prevalent household methods for disinfection. This option needs high energy, and the generation itself puts the load on fossil fuels and ultimately to the GHG emissions. Hence, it can be inferred that using heat energy or other conventional methods for water disinfection is costly and degrades the environment to a great extent. Also, it rather toxifies the water (carcinogenic compound formation in chlorination method). Renewable sources such as solar energy give the best outputs in such cases. If used efficiently, it reduces the cost and is completely safe and environment friendly. Renewable energy-based water disinfection comes as the valued solution (Richards and Schäfer 2010).

1.4 Scope of Chapter

Desalination of the sea water to get the fresh drinkable water is the dire need of an hour with the water scarcity and environmental concerns are haunting the world with rising natural calamities and climate change. UNO has already alarmed regarding the same and said that about 1800 million people across the globe will face severe water scarcity in the coming decade (WHO and UNICEF 200AD 2000; Fewtrell 2014). However, the desalination process is an energy intensive process which will further increase the fossil fuel consumption that will add to GHG emissions. Salts easily dissolves in water and the ionic bonds break and the atoms are then surrounded by the water molecules around it forming a homogeneous solution. Energy and the technology to desalinate water are both expensive, and this means that desalinating water can be pretty costly. To remove salts from this solution is tough and requires a lot of energy. To make the desalination process green and sustainable it is advised to go for renewable sources of energy. The desalination technologies coupled with renewable energy sources will prove to be the sustainable solution.

In the case of water disinfection process the traditional methods become inefficient in certain cases and if solar energy is used instead of them, it may become the key to the lock of all problems. There are millions of cases reported of diseases like diarrhoea primarily due to unsafe and impure water. Apart, millions die every year due to lack of access to safe and clean water. The prevailing conventional methods of disinfection are ineffective over economic and environment reasons. Chemical treatment, heat pasteurization, and filtration, require facilities, materials, and fuel that may not be readily available or feasible at all the locations. Renewable energy sources provides an alternative treatment option using solar energy, to inactivate pathogens through pasteurization and radiation effects. In this chapter we have discussions about solar energy both in the process of desalination as well as in the process of disinfection which could help researchers and experts to get all the required knowledge in this domain in a single content and further explore the research avenues. The chapter provides the perspectives on both the process and allied challenges in the domain (Abdel-Rehim and Lasheen 2005; Bohn et al. 2009; Shatat et al. 2013; Chandrashekara and Yadav 2017; Zhang et al. 2018).

2 Desalination

Solar energy based thermal desalination has been one of the novel approaches to applying renewable energy for getting fresh water. Solar energy-based desalination can either be categorized as a direct system where the solar energy is used directly to produce distillate in the solar collector or an indirect system where the solar system is combined with the other conventional desalination techniques; Multistage flash desalination, Vapor compression, Reverse osmosis, Membrane distillation and Electro dialysis. Solar energy is collected in the collectors while this is used in the desalination systems. Comparatively, the direct solar desalination needs larger areas and has less production rate than obtained with the indirect technologies. Both the technologies are discussed in the following paragraphs.

2.1 Direct Desalination Systems

2.1.1 Solar Still Desalination Process

Solar still method for desalination is one of the most economical and easiest ways to get fresh water from the sea feed water. In a solar still, the radiation directly falls on the sea feed water and provide the needed energy through solar radiation to evaporate the portion of feed water from the basin. The evaporated water gets collected at the top of the basin and eventually trickles down, condensing to be gathered as freshwater (Qiblawey and Banat 2008; Shekarchi and Shahnia 2019; Vigneswaran et al. 2019; Abd Elbar and Hassan 2020).

There are two different techniques employed in solar still water desalination. The first one employs the sun-tracking technique. In case the solar still rotates to capture the maximum amount of radiation. The possibility of receiving higher solar radiation increases with the movement of the solar still as it tracks the sun, and it leads towards higher production of fresh water. The second technique employs side mirrors; in this technique, the energy received from the sun is low; however, the presence of side mirrors causes multiple reflections and thereby secrete the energy in the still to a higher amount. Eventually, the higher energy causes higher evaporation and production rate (Kabeel and El-Said 2013, 2014).

Sohani et al. (2021) worked on innovative designs of solar still and has reported in-depth technical and economic analysis for the systems. They have investigated the prevalent techniques, sun tracking and using side mirrors, and eight case studies were considered for the experimental studies. They have monitored multiple components like; water temperature in the basin, fresh water production, cumulative yield, produced distillate, efficiency, and cost per litre. The set-up consisted of a solar still and a flat plate solar collector. These are connected with the help of the pipeline. There were two different reservoirs, one reservoir for the salty water attached to the solar still and another for water above the solar collector. Even there was a space for accumulation of the fresh water. The black colour was painted at the bottom of the solar still, which helped absorb a higher level of solar radiation. The experimentation concluded that when both techniques were applied together, the peak water temperature increased by 7.6 °C in the passive mode. Also, the production rates were said to increase by 43.2% for passive mode and 34.3% when in active mode. The overall cost per litre of water is reduced with the employed techniques compared to the conventional systems (Sohani et al. 2021).

2.1.2 Humidification-Dehumidification Desalination Process

Solar humidification-dehumidification desalination systems have two different water and air cycles that go through the humidifier and dehumidifier sections. The feedwater goes through the dehumidifier and then to the humidifier column in the water cycle. The concentrated brine solution obtained after the evaporation of the feed water leaves the humidifier. The cycle of air and water between the two-column converts the feed water into fresh water. There can be an open or closed cycle for both water as well for air. The configurations and design of heaters, humidifiers, and dehumidifiers make the primary elements of the system (Shekarchi and Shahnia 2019).

Yamali et al. (2008) reported a solar desalination system using the humidification–dehumidification process and investigated the influence on operational parameters. The reported setup of humidification-dehumidification processes studied comprised of a double-pass flat plate solar air heater, a humidifier, a water storage tank and a dehumidifying exchanger. Figure 2 shows the experimental setup and the thermocouple locations.

The desalination process with the humidification-dehumidification process worked in three major steps. The ambient air passes through the double pass flat plate solar heater and gets preheated in the first part. The air gets preheated in the first pass, and the preheated air is completely heated in the second pass. The heated air then goes to the humidifier, which gets humidified by the salt water from the storage tank. The humidifier consisted of multiple pads and a sprayer at the top. The water trickles down from the humidifier and goes back to the sump. The pump attached to the bottom of the storage tank supplies the water to the humidifier. The remaining salt water from the humidifier goes back to storage and is recycled. Lastly, the humified air goes into the dehumidifier, where the condensation occurs, and the fresh water is collected (Yamali and Solmus 2008).

In a similar work, Fath and Ghazy (2002) studied the performance of solar desalination using the humidification-dehumidification processes. The desalination system

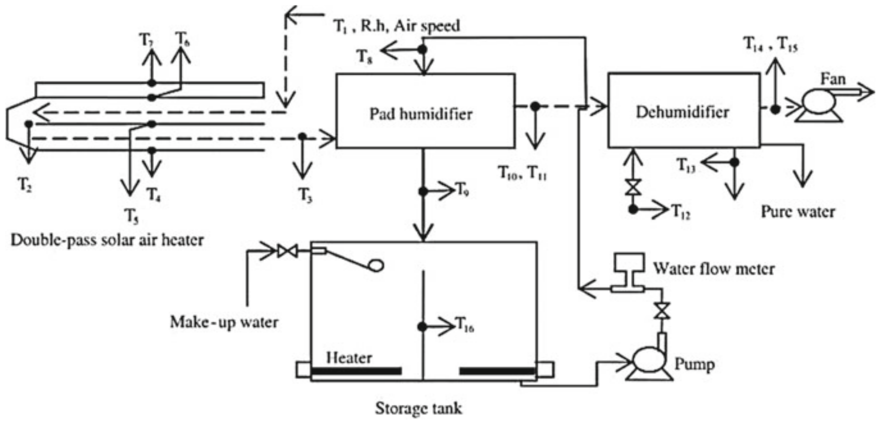

Fig. 2 Experimental set-up and thermocouple locations (Yamali and Solmus 2008)

used for the study consisted of a humidifier, dehumidifier, a circulating air-driving component, and a solar air heater. Different factors (environment, design and operational) affect the productivity of the desalination process. The environmental parameters were solar intensity, ambient temperature and wind speed, while design parameters included the solar heater insulation and the effectiveness of humidifier and dehumidifier. The operational parameters of the systems were water feed rate, air circulation rate and temperature. The increase in solar intensity and the ambient temperature improves productivity, while an increase in wind speed reduces the system productivity. The airflow rate improves the productivity only till 0.7 kg/s, beyond which no effect was observed. Overall it has been concluded that the system productivity is significantly influenced by the efficiency of the solar heater (Fathb and Ghazy 2002).

2.2 Indirect Desalination Systems—Thermal Process

Indirect solar desalination methods involves (1) collection of solar energy by using the conventional solar converting system and then (2) link it to a conventional desalination system. The electromagnetic solar radiation are converted to electricity using photovoltaic modules which then powers the desalination process. Desalination can be accomplished using multistage flash distillation, multiple effect evaporation, and/or vapor compression (Buros 2000).

2.2.1 Solar Multistage Flash Desalination

In a typical multi-stage flash desalination unit (MSF), the pressure in each unit was reduced steadily so that the feed water gets boiled repeatedly without adding more heat when it goes from one stage to another. MSF has been in use traditionally across the major regions around the globe, especially in the middle-east. In a multistage flash, desalination water is heated using the waste heat, and then it is flashed in different units by varying the saturation pressure. One such plant of 10,000 L capacity was installed and tested in 1983 at Safat, Kuwait. The detailed performance of this system is presented in the work by Moustafa et al. (1985). Solar multistage flash desalination will hold the major capital cost for solar energy collection and storage, including the solar panel collectors, PV modules, battery storage, and later for the desalination unit itself.

2.2.2 Solar Multi-effect Distillation

Preferably solar thermal plants are based on multi effect desalination for the reason being economical on energy consumption and has lower top brine temperature (TBT). Top brine temperature is an important part of the solar integrated techniques and regulating the TBT is essential to avoid the unstable operation. In a typical operation of multi effect distillation, water evaporates on the outside of the heated tubes in a single effect maintained at its saturation pressure. The evaporated water then moves on the next effect for additional vapor production. Sharaf et al. has reported the exergy and thermo-economic analysis for solar energy with different configurations of multi effect distillation desalination system. The comparison of multiple systems is presented for a case of 100 m^3/day of product distillate (El-Nashar and Samad 1998; Sharaf et al. 2011).

2.2.3 Vapor Compression Desalination

In a vapour compression desalination system, the feed water is heated by an external source, and then it is flashed. The vapours derived from the flash are then sent for compression, either by mechanical-vapour compression or thermos-vapour compression leading to higher condensation pressure and higher temperature. The compressed vapours are then deployed for heating in the subsequent stages. Helal and Al-Malek (2006) has given a detailed design of a solar-assisted mechanical vapour compression desalination unit specific to the remote areas of UAE. Thermo-vapor compressor-assisted MED has a lower specific power and total water production cost than the mechanical vapour-assisted MED (Helal and Al-Malek 2006).

2.2.4 Natural Vacuum Desalination Systems

Using the vacuum pump, vacuum desalination systems employ a unique technique of producing fresh water vapours from the saline water source at low temperatures. However, the system needs higher energy to produce a vacuum. The consumption can be reduced by naturally creating a vacuum in the flow systems. These systems are more options for small scale applications. Maroo and Goswami (2009) has reported such systems that uses the gravitational force and the atmospheric pressure to create a vacuum naturally. Details presented the theoretical analysis of the single and dual-stage solar-based flash desalination working with a natural vacuum. In a typical two-stage low-temperature natural vacuum desalination system, the vapours formed in the first stage gets condensed in the heat exchanger placed in the second stage. The heat rejected in the process helps vaporise the water in the second stage. However, the vapours from the second stage are condensed using an external condenser. Dual stage water performance was better than that of the single-stage system (Maroo and Goswami 2009).

2.2.5 Freeze Desalination

Freeze desalination is one of the emerging technology that overcomes the limitations of membrane-based and thermal energy-based desalination processes. The freezing desalination system needs to cool down the feed water well below its freezing temperature causing the pure water to form ice crystals. There are three types of freeze desalination naming; direct contact freeze desalination, indirect contact freeze desalination and vacuum-operated freeze desalination (Lu and Xu 2010; Rane and Padiya 2011; Williams et al. 2013).

Direct Contact Freeze Desalination

Desalination by freezing processes is based on the fact that, ice crystals formed by freezing the saline water are basically of pure water. In contradiction to the distillation method, crystallization or the freezing method needs the phase change of water from liquid to solid and hence consumes the latent heat that makes the process energy intensive. In case of direct contact freeze desalination the liquid refrigerant (usually n-butane) is brought in direct contact with the saline feed water in a way that the heat from the saline water is taken up by the refrigerant leaving behind the pure water ice crystals. These ice crystals can be then removed and purified to get the fresh water (Lu and Xu 2010; Williams et al. 2013).

Indirect Contact Freeze Desalination

The indirect contact freezing process contains a wall or a physical barrier separating the seawater and the refrigerant used for cooling. The main difference in indirect freezing compared to direct contact freezing is that the saltwater and the refrigerant do not directly come into contact. Mechanical refrigeration or various other means cause the ice to form on the surface, which has to be then removed. Removing ice from the heat transfer surface itself is a major drawback of this system (Lu and Xu 2010; Williams et al. 2013).

Vacuum Operated Freeze Desalination

In vacuum operated freeze desalination system, both the operation of evaporation and freezing are performed under vacuum. The feed water enters the system as the mix of ice and brine slurry, and water vapour are drawn out. At the start water is vaporized under high vacuum which in turn has a refrigerating effect that leads to ice crystals formation. These crystal are pure form of water that are melted and/or washed in the separate section. The compression of the vapour and driving the vacuum pump are the major heads of energy requirement for the system (Lu and Xu 2010).

2.2.6 Adsorption Desalination

In a typical arrangement the adsorption desalination system consists of (a) condenser, (b) adsorption beds (silica or zirconia) and (c) evaporator. This is a specific system where the water is having a double distillation effect. At first the adsorption cycle is undertaken by keeping the temperature low in the bed. The vapors from the evaporator are adsorbed in the bed. Secondly the water vapor so adsorbed is removed by increasing the temperature of the bed, this time circulating hot water. The removed vapors are now condensed to get the fresh water. First distillation effect is in the adsorption cycle and second in desorption cycle. Figure 3 gives the schematic of the adsorption desalination system that has two beds working alternate for adsorption and desorption cycle to get fresh water (Wu et al. 2010).

2.3 Indirect Desalination Systems—Membrane Process

2.3.1 Solar PV Powered RO Desalination

Reverse osmosis (RO) remains the demanding and dominating technology for water desalination. RO process needs the feed water to pass through the membrane module at high pressure, which is higher than the osmotic pressure of the membrane. The water passes under high pressure through the membrane module and rejects the salts. The rejection ratio of the salts is as high as 90%, while the water recovery is 50%. The primary attribute of Solar PV assisted RO desalination is a coupling of renewable energy in the operation of the RO desalination system. The membrane modules are prone to fouling and scaling. Sharon and Reddy (2015) has extensively reviewed the literature on Solar PV coupled RO systems that are installed across the globe. The quality of feed water, specifically salinity is the deciding factor for the life of the module and the required maintenance (Qtaishat and Banat 2013).

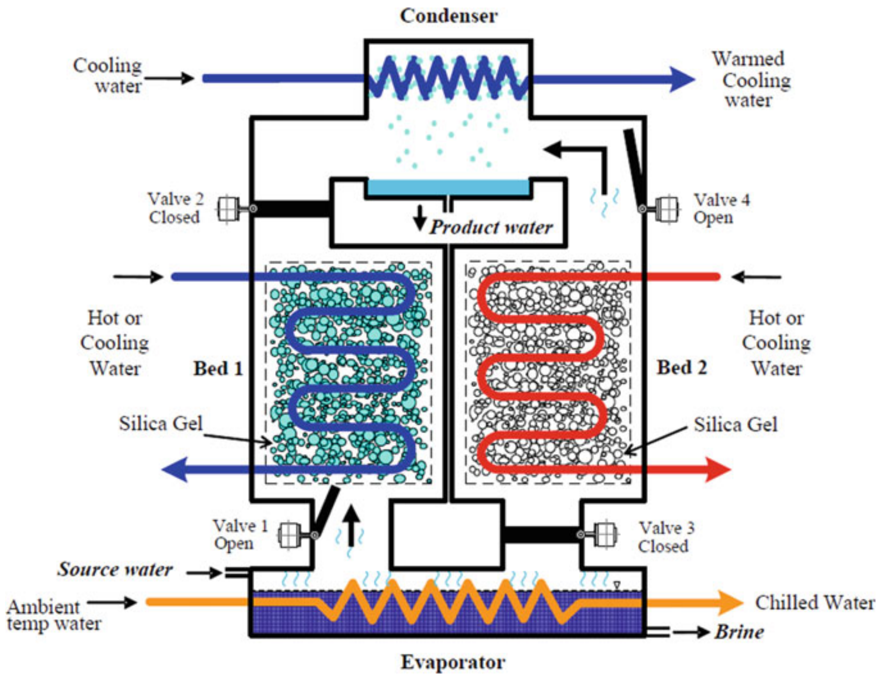

Fig. 3 Adsorption desalination system (Wu et al. 2010)

2.3.2 Solar Thermal Powered RO Desalination

As opposed to the solar PV in case of solar thermal powered RO desalination units, the energy produced by the solar is used to run the Organic Rankine Cycle which is then used to run the Reverse Osmosis unit. Solar thermal powered RO unit can be seen in the Fig. 4. Nafey et al. (2010) has studied on the thermos-economic analysis of solar thermal RO desalination unit where they explored the configurations for energy recovery. The study revealed that the energy recovery units positively reduced the production cost of water by 24% (Nafey et al. 2010; Sharaf et al. 2011).

2.3.3 Solar Powered Electro Dialysis (ED)

Dialysis is the process removing the excess waste. In case, salts are removed in the electro dialysis (ED) unit from the sea feed water. The ED unit comprise of compartments that are separated by cation and anion exchange membranes. These compartments are filled with the saline water. Under the influence of current across the membranes the positive ions are attracted towards the cation exchange membranes

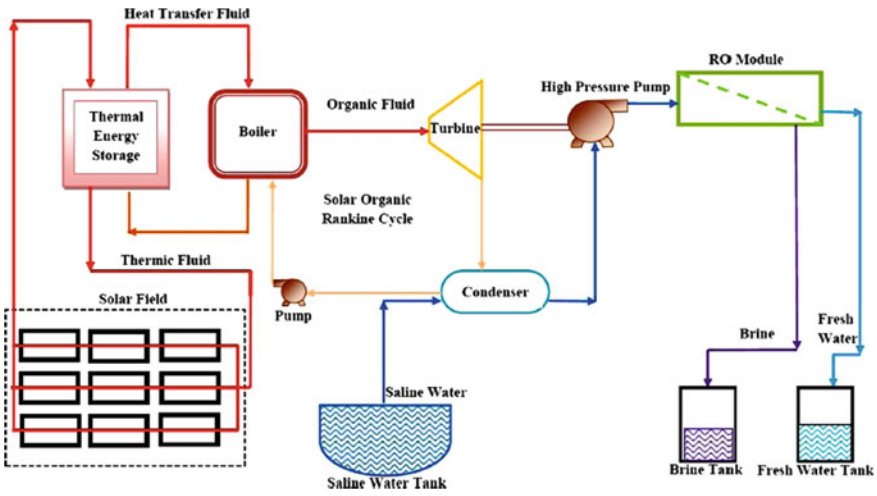

Fig. 4 Solar organic rankine cycle powered RO unit (Sharon and Reddy 2015)

while negative ions are attracted towards the anion exchange membrane. The accumulated ions across the membranes are removed leaving behind fresh water (Kuroda et al. 1987).

2.3.4 Solar Powered Membrane Distillation

Another set of membrane units that are coupled with solar is membrane distillation. In this process, water-vapour are only allowed to pass through the porous membrane. The hydrophobic membrane allows the separation due to the vapour pressure differences across the membrane. There are four types of membrane distillation processes: sweeping gas distillation, air gap membrane distillation, vacuum membrane distillation, and direct contact membrane distillation. Porosity, hydrophobicity and low thermal conductivity are the primary desired features for the membranes used in the process (Qtaishat and Banat 2013).

2.3.5 Solar Powered Forward Osmosis (FO)

Forward osmosis is a process in which the solvent molecules from the solution moves through the semi-permeable membrane towards the draw solution that is maintained at higher concentration than the feed solution. The higher osmotic pressure gradient yield high water fluxes and high feed water recoveries. McCutcheon et al. has presented a forward osmosis desalination process using ammonia and carbon dioxide system. The process used ammonium bicarbonate draw solution that extracted the water from a saline feed water across a semi-permeable polymeric membrane. When the ammonium bicarbonate was moderately heated, it decomposed into ammonia and carbon dioxide gas that were separated and recycled as draw solutes and are left with the fresh product water. It is recommended that the membranes used in forward osmosis should be able to with stand higher internal concentration polarization (McCutcheon et al. 2005).

2.4 Challenges and Perspectives

Desalination is going to be a crucial technology in the coming decade. The advent of solar coupled desalination units has brought new hope to get the process green and sustainable. Table 1 gives the advantages and limitations of the different desalination systems. Solar based desalination technologies provide clean and safe water but come with certain challenges (Greenlee et al. 2009; Ali et al. 2011):

(1) Scaling—Scaling remains the age-old problem dealing with the sea water. The depositions are hard to remove and hinder the overall desalination process. The higher temperature of operation leads to higher scale formation.
(2) Membrane Fouling—Fouling refers to the degradation of the membrane surface by the rejected molecules and impurities from the feed solution. Fouling reduces the flux output, and permeate can be of poor quality.
(3) Corrosion—The thermal process of desalination releases many gases during evaporation/flashing, which is the primary reason for corrosion. The performance of the heat transfer surface is greatly compromised because of corrosion.
(4) Brine Disposal—Desalination units reject highly concentrated saline water. Disposal of this to the oceans or other water bodies severely hamper the marine ecosystem. The higher concentration affects the aquatic flora and fauna.

Solar based desalination is one of the promising technologies for getting freshwater. The efficacy of the units has to be tuned with the local aspects. Any small improvement in efficiency would be a step towards conserving environmental or energy resources. Material science has a lot to explore on the front of reducing corrosion. Research in the domain of corrosion-resistant coating or novel composites will be appreciated. Other domains of renewable energy should also be explored and should be coupled with the desalination unit. It can be wind and or geothermal. These sources can be location specific and should be considered while deploying the desalination technology. Energy is the prime factor of costing in the desalination units. Hence getting local energy solutions and small scale durable desalination units should be looked upon rigorously. Membrane fouling is always a concern; improving the fouling resistance by developing responsive membranes that can have longer is sought topic in water treatment. Desalination is not a perfect technology, and this can have health issues for human beings as well. Desalinated water can be damaging to the digestive system. One has to take due care to have the need mineral content for healthy water for the society. Lastly, it should be survival for all and not survival for

Table 1 Comparing the pros and cons of desalination techniques

Desalination technique	Advantages	Limitations
Direct Desalination Techiques		
Solar Still	• Simple setup • Easily deployable • Low cost of construction • Low maintenance cost • High-quality water	• Bulky installation • Small scale production • Lower capacity • High labour cost • High water production cost • Needs large ground space
Solar HDH	• Simple • Low operation cost • Low maintenance cost • No need to pre-treatment • No scaling problem • Appropriate for remote areas and small units	• Small scale production capacity • Low capacity • Lower gain to energy used
Indirect Desalination Techiques—Thermal		
Solar multi-stage flash desalination	• Suitable for large scale production • Wide quality of feed can be treated • High-quality water is obtained	• High energy consumption • High possibility of Corrosion
Solar multi-effect distillation	• Comparatively low energy consumption • Lower temperatures operation possible • No pre-treatment required	• High possibility of Corrosion • High energy consumption
Vapour compression desalination	• High efficiency • Low energy consumption • Suitable for low-capacity applications • High-quality water is obtained • Low scale formation and corrosion	• Corrosion of compressor • High initial cost • Higher water production cost
Natural vacuum desalination systems	• A low-temperature heat source is sufficient	• High structures are required • Need to removal non-condensable gases formed during evaporation of water
Freeze desalination	• The energy required is low • Reduced corrosion and scaling	• Working with ice and water mixture is complex • Equipment is costlier • Freshwater is needed for washing off the salt on the surface of ice crystals before melting

(continued)

Table 1 (continued)

Desalination technique	Advantages	Limitations
Adsorption desalination	• Less fouling and corrosion • Less maintenance • High-quality water • Waste heat can be reused	• Energy-intensive • High GHG emissions
Indirect Desalination Techiques—Membrane		
Solar RO	• Simple • Low EC • Suitable for very small to large scales • Ideal for remote areas • Permeate water quality with less than 500 ppm	• Feed water quality matters • Needs pre-treatment of water • High-pressure pumps required • Fouling • High cost for unit and maintenance
Solar ED	• Operation at lower pressure in comparison to RO • Suitable for SFW with a salinity of less than 5000 ppm • Permeate water quality with less than 600 ppm	• Needs pre-treatment and posttreatment for drinkable water production
Solar MSF	• Suitable for medium and large-scale desalination plants • Ideal for cogeneration from waste heat in power plants • No need for pre-treatment of water • Independent of SFW quality • Permeate water quality with less than 10 ppm	• Consumes a high amount of thermal and electrical energies • Needs high top brine temperature (90–110 °C), high capital, and maintenance cost
Solar MED	• Suitable for medium and large-scale plants • Ideal for cogeneration from waste heat in power plants • No need for pre-treatment of water • Independent of SFW quality • Lower required top brine temperature (70 °C) • Permeate water quality with less than 10 ppm	• Consumes a high amount of thermal and electrical energies • High capital and maintenance cost

Abbreviations: EC, energy consumption; GOR, gained output ratio; MED, multi-effect distillation; MSF, multi-stage flash; RO, reverse osmosis; SFW, saline feed water; WPC, water production the fittest. The overall life cycle assessment of the brine and its impact assessment on the marine ecosystem should be taken to understand the effect of technology and move towards sustainability.

3 Solar Disinfection

3.1 Need and Development of Solar Disinfection

Consuming contaminated water poses a serious threat to human health worldwide. This is a grave problem specifically in third world countries and SAARC nations wherein healthcare resources and water treatment technologies are scarce. In developing countries, the primary source of water comes through rivers, side streams, ponds and lakes and these are also used for completing all the activities from agriculture to watering cattle to the daily requirements of the human race (WHO and UNICEF 200AD 2000). People in developing nations don't have any alternative sources apart, and the same sources are exploited for getting potable water for consumption. The water bodies are also getting polluted due to wide human activities and industrialization. Wherever the water distribution and treatment infrastructure is scarce, the same streams in the least treated form is used for consumption. The contamination caused seriously affects the health of flora, fauna and human beings. Specifically, children are the ones who are more susceptible to the ill effects of impure water.

Waterborne diseases infections come through a variety of bacteria, viruses and parasites. These come through a large group of causative agents and are followed by parasites and bacteria. Analysing these organisms require expensive analytical methods. However, as an indirect method, it is easier to check the organisms indicating the faecal pollution in the water. These organisms do not always transmit through the water but poor hygiene (Curtis et al. 2000).

Furthermore, secondary contamination of drinking water due to incorrect water storage and usage is frequently observed. Therefore, the need is sought for interventions to improve water quality while enhancing the general ways of hygiene. Waterborne diseases can be transmitted through multiple routes. Figure 5 showcases the possible transmission routes. Diarrhoea is a common problem that is caused by pathogens and easily transmits to humans through person-to-person contact, flies or through inadequate hygiene behaviour (e.g. not washing the hands). Improving hygiene itself has a considerable effect on the population's health. Apart from water treatment and improved water quality is necessary for building strong resistance to infections and curd the transmission (Ise et al. 1994; Swiss Federal Institute for Environmental Science and Technology (EAWAG) 2002).

As per the World Health Organization's evaluation, impure water and scarcity of freshwater supply are the predominant reason for around 80% of all the infectious diseases in the world. Water is essential for the cooling effect as well as excreting the

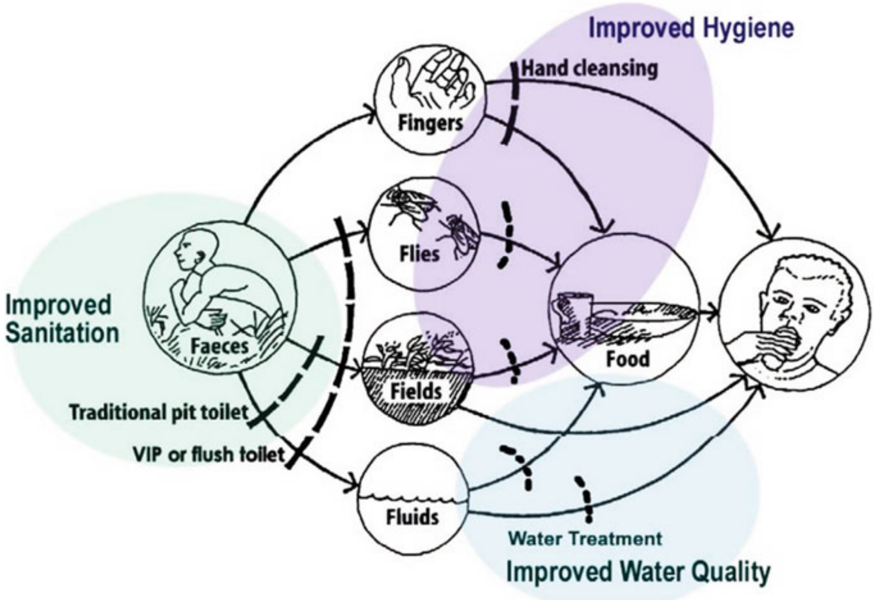

Fig. 5 General cycle showing transmission routes of diseases due to improper hygiene

toxins from the body. As per the United Nations Global Drinking Water Quality Index Development and Sensitivity Analysis Report, microbial load analysis and treatment are crucial factors ensuring the drinking water's safety (Rickwood and Carr 2007). Dissolved salts, alkalinity, toxic metals in water must also be taken for remediation and microbial loads. Photocatalytic degradation, Fenton process and other visible to UV light assisted processes to degrade the water pollutants (Herrera Melián et al. 2000; Rincón and Pulgarin 2004; Rizzo et al. 2014; Vyatskikh et al. 2018). Water bodies around the globe are under stress due to the rise in the population and the demands therein. Water disinfection is one of the essential components to reduce waterborne diseases. The advent of renewable energy-based water disinfection can lead to an economical way of providing safe water for all (Khan et al. 2015).

3.2 Implications of the Solar Disinfection (SODIS) Method

Solar Energy based disinfection popularly called the SODIS method employs the reactor that collects the solar radiation and cleanse the feed water. It is the simplest of water treatment technology that can be readily used at the household level. Primarily SODIS is for reducing the microbial load and improves the quality of drinking water thereby reducing the risk of contracting water borne disease. The quality of disinfection is dependent on the performance of the SODIS-reactor that is dependent on the area for photon collection and the pathlength that the radiations has to be pass through the water. The solar assisted disinfection reactors are more opt for the isolated locations in emergency situations especially during the times of flooding or earthquake where the access to safe drinking water will be an issue. SODIS bags is a novel approach in the area which can be easily transported and stored. These bags can be made available for the personal usage and can be used for SODIS disinfection. These bags holds about 1–2 L of water (with low turbidity) and is let exposed to the sunlight for a certain time (recommended 6 h) depending on the site and weather conditions. SODIS is the simple and extremely low cost method for improving the microbial quality of drinking water. The method does not stand as the replacement for the access to safe drinking water as it does not ensure to complete remediation of water (Swiss Federal Institute for Environmental Science and Technology (EAWAG) 2002; Amin and Han 2009; Byrne et al. 2011; Verma and Prasad 2013; Dessie et al. 2014).

Mcguigan et al (1999) in his editorial note talked about the SODIS and use of sunlight to decontaminate drinking water in the developing countries. It was noted that how simple exposure to sunlight can be more economical, easier and simplest of an alternative to decontaminate the water. Similar system containing the array of transparent pipes facing to the sunlight would supply the water to complete village however the cost of installation, supply and the other factors disturbs the economics. It was noted that there is a strong synergy between the optical and thermal inactivation processes, temperature dictates the inactivation process. Table 2. provides the role of SODIS in inactivating different pathogens. (McGuigan et al. 1999).

Following factors should be ensured to enhance the efficiency of SODIS.

- Place the SODIS bags/PET bottles horizontally or at a flat angle facing the sun
- Use the raw water that has lower turbidity
- Place bottles on a sheet, roof top, or the ground which reflects sunlight
- Start exposing the bottles as early in the morning as possible, expose the bottle for about 6 h of bright sunlight
- Make sure that no shadow falls on the bottles.

In one such study Giannakis et al (2015) studied the environmental considerations on solar disinfection of waste water. The study was more focused on the effect analysis of different parameters like intensity of radiation, disturbance in the light delivery and the happenings during storage post-irradiation. It was concluded that based on the bacterial inactivation curves that when the illumination was intermittent it unevenly prolongs the exposure period. Hence extended illumination time is expected during such conditions. The disinfection kinetics was best described in the three phase; (a) first is induction/lag phase as the solar radiation begins (b) second is the monotonous inactivation period, this is prime phase where most inactivation is completed and (c) third is the tailing end when the rate is again lower towards closing. Overall it was understood from the study that tuning the parameters of the SODIS unit has to have a local oriented approach to make it more opt to the applications (Giannakis et al. 2015).

Table 2 Role of SODIS for various pathogens

Pathogens	Effect of SODIS
	Load reduction >99%
Bacteria	• E.coli • Vibrio cholera • Salmonella spp. • Shigella flexneri • Shigella dysenteriae • Campylobacter jejuni • Yersinia enterocolitica • Enterococcus feacalis Inactivation time of ~1 day
	Load reduction
Viruses	• Rotavirus 70–90% • Coliphages >90% • Encephalomyocarditis virus—Ineffective • Adenovirus—Ineffective • Polio virus—Ineffective Inactivation time of 1–2 day
	Load reduction
Protozoa	• Giardia >99% • Cryptosporidium 50–90% • Amoeba > 99% Inactivation time of up to 10 h to 3 day
	Load reduction
Fungi	• Ascaris suum > 90% • Fusarium solani ~70% • Candida albicans >90% Inactivation time of ~1 day

SODIS for waste water treatment plant was evaluated by Gutiérrez-Alfaro et al (2018). The evaluation was on the feasibility of integrating the solar disinfection technology along with the urban wastewater treatment plant having the processes based on microalgae biotechnology. The algal biotechnology consisted of an Up flow Anaerobic Sludge Blanket (UASB), High Rate Algal Ponds (HRAP) and a Dissolved Air Flotation (DAF).The author studied the efficiency of the SODIS process for the inactivation of *Escherichia coli, Enterococcus spp. and Clostridium perfringens* as indicator microorganisms with effect of irradiance and temperature. SODIS technology was found to be more effective for the two; *Escherichia coli*, *Enterococcus spp* while DAF is better for *Clostridium perfringens*. It was concluded that the adding the SODIS unit with the WWTP improves the quality of treated water and increases the possibility of reuse (Gutiérrez-Alfaro et al. 2018).

SWINGS, a tie-up between the European Union and India for taking up projects on implementing the low-cost sustainable technologies for water treatment, disinfection and reuse targeting the population of rural India. Álvarez et al (2017) has reported on the SWINGS project on the constructed wetlands and solar-driven disinfection technologies for rural India. The study focused to provide the sustainable wastewater treatment solution and reclamation of water resources. The study showcases the results from the two pilot plants one at Aligarh Muslim University, AMU and other at Indira Gandhi National Tribal University, IGNTU. The solar driven disinfection unit at IGNTU was able to produce the water quality that can be reused in for agriculture and irrigation purpose (Álvarez et al. 2017).

3.3 Visible Light Assisted Disinfection

Photocatalysis is the most cited way for pollutant degradation in water and wastewaters. Visible light holds a substantial range in the solar spectrum, making it more option to use it in water disinfection. Recently photocatalysts have been widely tested for their property of water disinfection. You et al. (2019) has given an extensive review on the topic of visible light active (VLA) photocatalysts for water disinfection. The review has reported the microbial disinfection efficiencies, recyclability characteristics, and disinfection mechanisms of different photocatalysts explored in the literature (You et al. 2019).

In a typical photo-catalytic mechanism, when the semiconductor material is irradiated with the visible light radiations, photons with higher energy than the bandgap of catalytic material are absorbed, and the electron from the valance band jumps to the conduction band. The process leaves behind a hole in the valence band and an electron in an excited state in the conduction band that is now available on the catalyst's surface. These electron–hole pair now acts as the base for generating radicals, hydroxyl and superoxide, through the reaction with oxidants and adsorbed water molecules. The reactive oxygen species so produced enter the microbial cells and cause inactivation. The susceptibility of different microbes to photocatalytic disinfection is not the same and is in this order: viruses > bacteria > yeasts > moulds (Bogdan et al. 2015). The precise mechanism for the inactivation is still not clear and can be further taken for research. Figure 6 gives the probable mechanism for the inactivation.

Although there is a wide pool of semiconductor materials, not all of them has the necessary properties to cause the inactivation of microbes. In recent times, the focus has been on developing semiconductor heterostructures that assist the charge transfer between the diverse photocatalysts. Doping with low-level impurities is another way to induce charge transfer.

3.4 Challenges and Perspectives

SODIS is undoubtedly one of the most simple, cheap and effective solutions for disinfecting the water and reducing the microbial load. The implications and outreach of the technology are high because the location does not constrain it.

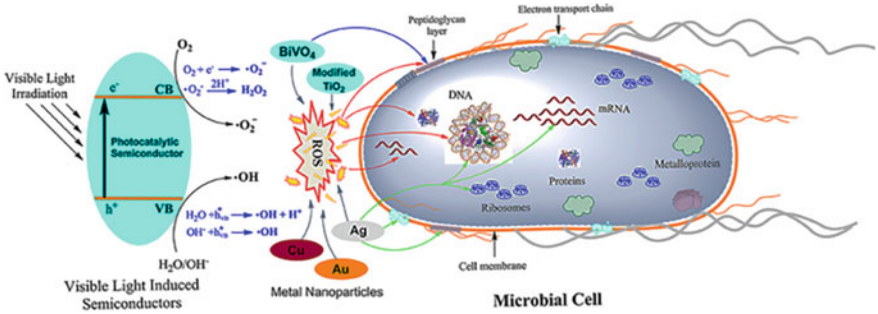

Fig. 6 The probable antimicrobial mechanisms of different photocatalytic semiconductors and their cellular targets. ROS—reactive oxygen species (You et al. 2019)

No process is full proof, and one needs to tune to the requirement of the process. Multiple parameters actually impact the SODIS process (Rincón and Pulgarin 2004; Blanco et al. 2009; Malato et al. 2009). These are.

(a) Water quality (pH, turbidity, chemical species)—the quality of water is crucial for the disinfection process. Content of any suspended solid particles, chemical species, organic matters or faecal material can add to the turbidity. The presence of these materials hinders the disinfection process. Some preliminary local filtration has to be carried out, be it sand filter/carbon filter to remove the unwanted materials before going for disinfection
(b) Nature of microorganism and microbial load—different organisms has different resistance, and the survival depends on the structure attacked during disinfection. The disinfectant can break through the cell wall/membrane and cause damage to the different elements of the cell (McGuigan et al. 1999; Byrne et al. 2011). This is the part of research where we need to look for the ability of SODIS and its limitations to handle some microbes.
(c) Exposure time for disinfection (refers to concentration and contact time). In abrupt weather conditions, when the sunlight will be less, the exposure time prolongs, and the disinfection process needs more time. Monitoring the microbial load is important in such cases.
(d) Temperature has a positive influence on disinfection. The disinfection efficiency improves with an increase in temperature. Developing the relation of sunlight intensity, exposure time, and microbial load concentration can set the guidelines for the applicants using the technology.
(e) Co-presence of other elements compounds might react or decompose during the process of disinfection and should be avoided. However, the disinfection process does not eliminate these components
(f) Monitoring the microbial load is crucial in understanding the progress and efficacy of the disinfection process. Faecal indicators reflect the presence of faecal contamination in the water and infer the load of microbes present. The

model organisms can be used to indicate pathogenic presence and behaviour, respectively.

4 Conclusion

Desalination and disinfection of water using solar-based technologies have added a newer avenue of looking at these processes. It is the step towards a sustainable and greener approach to get fresh, clean and safe water for all. Solar energy coupling with the desalination units has opened the arenas of innovative design and improved the efficacy of desalination so does the usage of renewable energy. Energy storage will dictate the future of these technologies. Solar energy comes as a feasible option for safe water, improving community health and providing a sustainable solution. Water disinfection has been conventionally done for cleaning water from micro-organisms in the water. However, chlorine-based and chemical-based disinfection that are common in practice has environmental concerns and health effects. Boiling remains as the energy intensive option. Solar-based disinfection has come out as the most efficient, eco-friendly, and economical water disinfection. Renewable energy-based water treatment will be the area of focus for the coming decades and will heavily impact the water remediation sector.

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